Chapter 3

THE BUILDINGS SECTOR

3.1 INTRODUCTION

Energy is used in buildings to provide a variety of services such as lighting, space heating and cooling, refrigeration, and electricity for electronics and other equipment. In the U.S., building energy consumption accounts for nearly one-third of total primary energy consumption and related greenhouse gas emissions. The cost of delivering all energy services in buildings (such as cold food, lighted offices, and warm homes) will be over $220 billion in 1997.

Our analysis shows that substantial reductions in future greenhouse gas emissions can be realized through the use of more energy-efficient technologies that save society money. In addition, these technologies often supply other benefits beyond energy, carbon, and dollar savings, including the following: (1) improved indoor environment, comfort, health, and safety, (2) reduced noise, (3) improved process control, and (4) increased amenity or convenience (Mills and Rosenfeld 1994). These indirect benefits, while difficult to quantify in economic terms, can be even more important than the energy cost savings, particularly when they improve the comfort of homeowners or the productivity of workers.

This chapter describes our detailed assessment of the achievable cost-effective potential for reducing carbon dioxide emissions in 2010.[1] We calculate carbon, energy, and dollar savings associated with adoption of more energy-efficient technologies. In addition, this chapter qualitatively describes the role of research and development (R&D) in providing a stream of advanced building technologies and practices after 2010 that will enable continued reduction in energy use and greenhouse gas emissions.

All costs in this chapter are reported in 1995 U.S. dollars (1995$). Carbon dioxide emissions are reported in terms of their carbon equivalent. To convert carbon dioxide units at full molecular weight into carbon units, divide by 44/12 or 3.67. For further information on emissions data, see EIA (1995).

3.2 PROVEN AND NEAR-TERM TECHNOLOGIES

In developing scenarios of carbon dioxide emissions for the residential and commercial buildings sectors, we drew from a wide range of information and models available on end-use energy demand, consumption, efficiencies, and technologies (see Section 3.7 References). Using this information, we developed a spreadsheet model that incorporates the work of existing models and analyses as parameters while providing a transparent framework to display assumptions, calculations, and results. This model, developed specifically for the project, is described in Appendix C-1.

3.2.1 Generic Assumptions

Our approach is based on a stock accounting framework of building and equipment types. For all scenarios, base case growth in households and commercial floorspace tracks historical trends. This results in a net total 2010 stock that is greater than 1997 levels by 15% and 12% in residential and commercial buildings, respectively, taking account of new building construction and retirement of existing stock. Retrofit or replacement of existing "shells" (walls, roofs, windows, doors) and equipment is a function of their average lifetimes. We assume that, on average, residential and commercial building shells last 100 and 50 years, respectively, and thus only a small portion of buildings are replaced during the study period with a much larger fraction undergoing some shell retrofit. In contrast, average equipment lifetimes range from one year (for lights) to 20 years (for furnaces). All equipment with lifetimes significantly less than the forecast period (13 years), such as residential lighting, will be replaced but only a portion of the equipment with lifetimes comparable to or longer than the forecast period will be replaced. The combination of shell and equipment turnovers results in four categories of buildings in our model: (1) old buildings with old equipment; (2) old buildings with new equipment; (3) retrofit building shells with new equipment; and (4) new buildings with new equipment.

After characterizing the building stock in 2010, we calculate energy intensities (end-use energy per household or per unit floor area) for all end-uses for 1997 and, in our initial assessment, use the factors from the Energy Information Administration's (EIA's) *Annual Energy Outlook* (AEO97) to establish baseline values in 2010 (EIA, 1996). In general, average 2010 energy intensities are lower than those in 1997, reflecting technology improvements that provide the same level of energy service with less energy.

We multiply each equipment end-use energy in 1997 (e.g. water heating, cooling, lighting) in the four building categories by applicable energy intensities to derive future energy use. If more services per household or unit of commercial floorspace are required by consumers, or if the size of the overall building stock (relative to 1997) increases, this will increase the energy required to provide energy services. Thus, energy demand in 2010 is a product of the rates of change in energy service requirements within the buildings and changes in the overall growth in the building stock.

To derive energy-efficiency scenarios, we use the cost of energy intensity improvements and electricity and fuel prices in 2010 to assess cost-effective reductions in energy use. For the residential buildings, the efficiency scenarios also account for fuel switching (the impact of switching from electric to gas water heaters, clothes dryers, and ranges) and for the use of high-albedo roof materials (“cool roofs”) to reduce cooling requirements (see Appendix C-4). For the commercial sector, we include the analysis of cool roofs but do not include fuel switching.

3.2.2 Scenario Definitions

The model was used to generate results for three scenarios: "business-as-usual" (BAU), "efficiency" (EFF), and "high-efficiency/low-carbon" (HE/LC). The business-as-usual scenario was calibrated to the National Energy Modeling System (NEMS) model outputs, so that it corresponds to the same 2010 baseline currently used in AEO97.

For both the efficiency and high-efficiency/low-carbon scenarios, we first calculate the 2010 energy use assuming 100% implementation of maximum cost-effective efficiency improvements in new building shells and equipment. This maximum efficiency potential was calculated as the difference between the energy intensity of the most cost-effective energy-efficiency technologies currently available, and the energy intensity of new equipment in 1997. The maximum cost-effective efficiency improvements are based on detailed studies; measures were not included if they had a cost of conserved energy greater than the average cost of purchased fuel or electricity.[2] For comparative purposes, we have also analyzed a "frozen efficiency case" in which the efficiencies of all new equipment and building shell measures are kept at 1997 levels of new products.

We then derive the efficiency scenario by assuming that 35% of the difference in total energy savings between the business-as-usual case and the maximum cost-effective efficiency case is achieved. For the high-efficiency/low-carbon scenario, we assume a 65% achievement rate. Assessments of future policy impacts are inherently speculative. We chose these implementation factors based on a review of program experience (Brown 1993, Brown 1994) and use of our judgment regarding how energy service markets would respond to policies and programs associated with aggressive commitments to reduce carbon emissions. We began with Brown's (1993) conclusion that about half of the techno-economic potential could be captured given coordinated efforts on minimum efficiency standards, utility programs, and information programs. Our choice of 35% and 65% brackets this result. The lower number (efficiency case) matches Brown's most pessimistic sensitivity case, while the higher number (high-efficiency/low-carbon case) corresponds to aggressive implementation of non-price policies combined with the assumption of policies such as a cap and trade system for carbon and other economic signals that would support these aggressive efforts. Brown did not address price signals in his report, so the most optimistic scenario he considers reaches about 60% of the maximum economic potential. We believe that the addition of these price signals under an aggressive policy regime is consistent with our assumption of an achievable efficiency level to 65%. Details of the scenario calculations are provided in Appendix C-2.

Emissions factors for fuel-fired end-uses are taken from EIA (1995), while electricity sector emissions factors are calculated in the utility section of this report. Electricity carbon emissions factors in the business-as-usual case are 163 gC/kWh of electricity at the meter. In the efficiency case, the marginal generating plants are high-efficiency gas-fired combined cycle plants, which reduces the carbon saved from each kWh to 95 gC/kWh. In the high-efficiency/low-carbon case, the carbon saved per kWh (relative to the business-as-usual case) increases to 127 gC/kWh because of changes in the electricity supply system brought about by the carbon permit price. (See Chapter 6, Tables 6.6 and 6.7, and accompanying discussion for an explanation of this factor.)

3.3 SCENARIOS FOR THE YEAR 2010

Three scenarios are presented for residential and commercial buildings carbon emissions in 2010: business-as-usual, efficiency, and high-efficiency/low-carbon. Tables 3.1 through 3.3 and Figure 3.1 provide the main results for the three scenarios.

On Figure 3.1, the x-axis shows the percent change in carbon emissions from 1990 levels. The y-axis shows total cost of energy services in 2010, expressed on an annual basis. This cost includes the annualized incremental cost of efficiency improvements beyond the business-as-usual case plus the cost of electricity and fuel purchases.

Table 3.1 Primary Energy Use in the Buildings Sector (quads): 1990-2010

End-Use/Fuel	1990	1997	2010 Business-as-Usual Case	2010 Efficiency Case*	2010 High-Efficiency/Low-Carbon Case*
Residential:					
Electricity	10.2	11.9	13.0	12.0 (7.1%)	10.8 (16.9%)
Fossil	6.5	7.2	7.4	7.3 (1.4%)	7.2 (2.6%)
Subtotal	16.7	19.1	20.4	19.4 (5.0%)	18.0 (11.8%)
Commercial:					
Electricity	9.4	10.6	11.4	10.7 (6.0%)	9.7 (14.9%)
Fossil Fuels	3.8	4.0	4.2	4.0 (4.7%)	3.9 (8.7%)
Subtotal	13.2	14.6	15.6	14.7 (5.6%)	13.5 (13.5%)
Sector Total:					
Electricity	19.7	22.5	24.3	22.7 (6.6%)	20.6 (15.2%)
Fossil	10.2	11.2	11.7	11.4 (2.6%)	11.1 (4.8%)
Total	29.9	33.7	36.0	34.1 (5.3%)	31.7 (11.9%)

* Numbers in parentheses represent percent reductions from the business-as-usual (BAU) case.

Note: Table does not include effects of building-sector fuel cells. Numbers may not add to the totals due to rounding.

Table 3.2 Carbon Emissions in the Buildings Sector (MtC): 1990-2010

End-Use/Fuel	1990	1997	2010 Business-as-Usual Case	2010 Efficiency Case*	2010 High-Efficiency/Low-Carbon Case*
Residential:					
Electricity	162	183	213	202 (5.4%)	185 (13.5%)**
Fossil Fuels	91	102	106	104 (1.5%)	102 (2.9%)
Subtotal	253	285	319	306 (4.1%)	287 (10.0%)
Commercial:					
Electricity	150	163	187	178 (4.7%)	165 (11.8%)**
Fossil Fuels	59	62	65	62 (4.5%)	59 (8.4%)
Subtotal	209	225	252	240 (4.7%)	225 (10.9%)
Sector Total:					
Electricity	312	346	401	380 (5.1%)	350 (12.7%)**
Fossil Fuels	150	164	170	166 (2.7%)	162 (5.0%)
Total	462	511	571	546 (4.4%)	511 (10.5%)

* Numbers in parentheses represent percent reductions from the business-as-usual (BAU) case.

** A portion of the reduction in carbon emissions associated with the high-efficiency/low-carbon case is due to changes in the electricity generation mix prompted by the charge of $50/tonne of carbon.

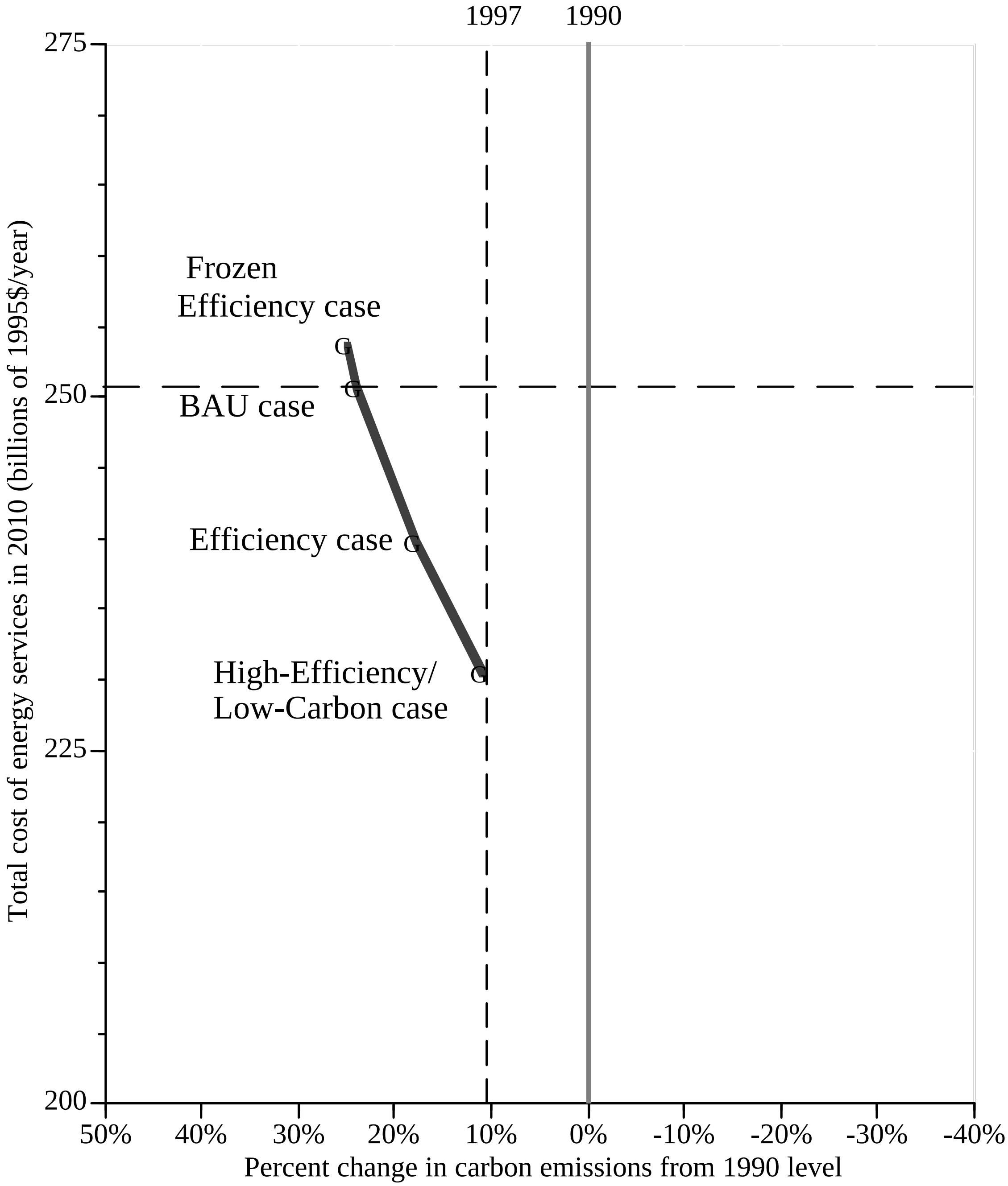
Note: Table does not include effects of building-sector fuel cells. Numbers may not add to the totals due to rounding.

Table 3.3 Annual Total Cost of Energy Services in the Buildings Sector (billions of 1995$): 1990-2010

	1990	1997	2010		
			Business-as-Usual Case	Efficiency Case	High-Efficiency/Low-Carbon Case
Annual Fuel Cost	$226	$228	$251	$233	$218
Annual Incremental Cost of Efficiency Improvement	--	--	$0	$7	$13
Annual Total Cost of Energy Services	$226	$228	$251	$240	$231

Note: All costs are expressed in 1995 dollars (1995$). The annual total cost of energy services equals the sum of annual fuel cost and annualized incremental cost of efficiency improvement (i.e., the cost of purchasing and operating higher-efficiency equipment in the efficiency and high-efficiency/low-carbon scenarios). Table does not include effects of building-sector fuel cells.

Figure 3.1 Relationship Between Costs of Energy Services and Carbon Emissions in the U.S. Buildings Sector in 2010



1990 U.S. buildings sector C emissions = 462 MtC

1997 U.S. buildings sector C emissions = 511 MtC

Notes: A portion of the reduction in carbon emissions associated with the high-efficiency/low-carbon case is due to changes in the electricity generation mix prompted by the charge of $50/tonne of carbon. Total cost of energy services includes costs of purchasing fuel and electricity as well as the annualized incremental cost of efficiency improvements relative to the business-as-usual case. Figure does not include effects of building-sector fuel cells.

3.3.1 Business-as-Usual Scenario

The business-as-usual scenario provides an estimate of energy demand and carbon emissions in 2010 in the absence of any new efforts to promote the more rapid development, purchase, and use of high-efficiency technologies in the residential and commercial buildings sectors. In this scenario, energy demand grows by 20% from 1990 and 7% from 1997 levels (from 29.9 and 33.7 quads in 1990 and 1997, respectively, to 36.0 quads in 2010). Carbon emissions in 2010 are 24% and 12% higher than in 1990 and 1997, respectively (increasing from 462 MtC in 1990 and 511 MtC in 1997 to 571 MtC in 2010). Carbon emissions grow faster than primary energy use in the business-as-usual case, mainly reflecting changes in the fuel mix used to produce electricity. Because there is no accelerated efficiency improvement in the business-as-usual scenario, the total annual cost of energy services ($251 billion) is only the annual energy cost paid by consumers during that year.[3]

In the residential sector, energy use in the business-as-usual scenario grows from 16.7 quads in 1990 and 19.1 quads in 1997 to 20.4 quads in 2010, (a 22% and 7% increase over 1990 and 1997 levels, respectively). Carbon emissions are projected to grow from 253 MtC in 1990 and 285 MtC in 1997 to 319 MtC over the same time period (a 26% and 12% increase from 1990 and 1997, respectively). The increase in emissions in this sector is due to moderate growth in the residential building and equipment/appliance stock coupled with substantial growth in miscellaneous energy use. For analytical purposes, we divide these miscellaneous uses into three electricity categories (electronics, motors, and heating) and two non-electricity categories (natural gas and oil/other petroleum products).[4]

Emissions from the rise in miscellaneous electricity use grow nearly four times as fast as the residential sector as a whole, resulting in the share of miscellaneous electricity use jumping from 23% of total demand in 1997 to 29% in 2010. There exist important problems in the way that EIA defines and calculates the size of the miscellaneous end-use which leads to uncertainties in the correct values. It would be possible with more research to allocate some of the miscellaneous energy to the existing end-uses and to new ones; for example, electricity consumed by furnace fans should be treated as space heating. New end-uses for televisions and dishwashers might be appropriate. Even if the energy is not correctly allocated among the end-uses, the estimates of the savings potential will not significantly change. More research is needed to evaluate the amount of energy used for specific tasks as well as the technologies available to reduce energy use within the miscellaneous end-use category (for the most detailed recent assessments, see Sanchez (1997) and Koomey and Sanchez (1997)).

Despite these increases in service demand, total residential energy demand will be tempered through improvements in key residential equipment efficiencies, mainly due to implementation of appliance efficiency standards between 1997 and 2010. In particular, energy intensities for gas and electric water heaters, freezers, and refrigerators decrease by 34%, 29%, 18% and 15%, respectively, over the period. Had these declines in intensities not occurred, energy use for these end-uses would have been 14% greater in 2010 than the current business-as-usual scenario results. Residential sector energy use and carbon emissions in 1997 and 2010 are shown in Figure 3.2 below.

In the commercial sector, there are even greater problems in the way that EIA defines and calculates the size of the miscellaneous end-use than in the residential sector. Even given these accounting uncertainties, our assessment of the opportunities for efficiency improvements is almost certainly conservative.

In the commercial sector, energy use in the business-as-usual scenario is projected to grow by 18% from 1990 and 7% from 1997 to 2010 (13.2 quads in 1990 and 14.6 quads in 1997 to 15.6 quads in 2010). Carbon emissions are projected to grow by 21% from 1990 and 12% from 1997 to 2010 (209 MtC in 1990 and 225 MtC in 1997 to 252 MtC in 2010). Miscellaneous electricity end-uses such as motors, electronics, and small appliances are expected to increase from 9% of total commercial sector energy use in 1990 to 20% in 2010. This growth, which accounts for over 70% of the growth in carbon emissions in commercial buildings, offsets nearly all carbon emission reductions from energy-efficiency improvements in other end-uses. Miscellaneous energy use in the commercial sector is even less well understood than in the residential sector. As mentioned above, more analysis and data collection are needed to improve our understanding of this end-use category.

Although energy use from office equipment is expected to grow by 22% over the period, its share of energy use in commercial buildings remains relatively small, growing to 6% in 2010. The greatest increases in energy efficiency in the commercial sector come from continuing improvements in space conditioning (due to improved equipment and controls) and water heating systems. Commercial sector energy use and carbon emissions in 1997 and 2010 are shown in Figure 3.3 below.

Figure 3.2 Residential Sector Primary Energy Use and Carbon Emissions in 1997 and 2010 by End-Use for the Business-As-Usual Scenario[5]

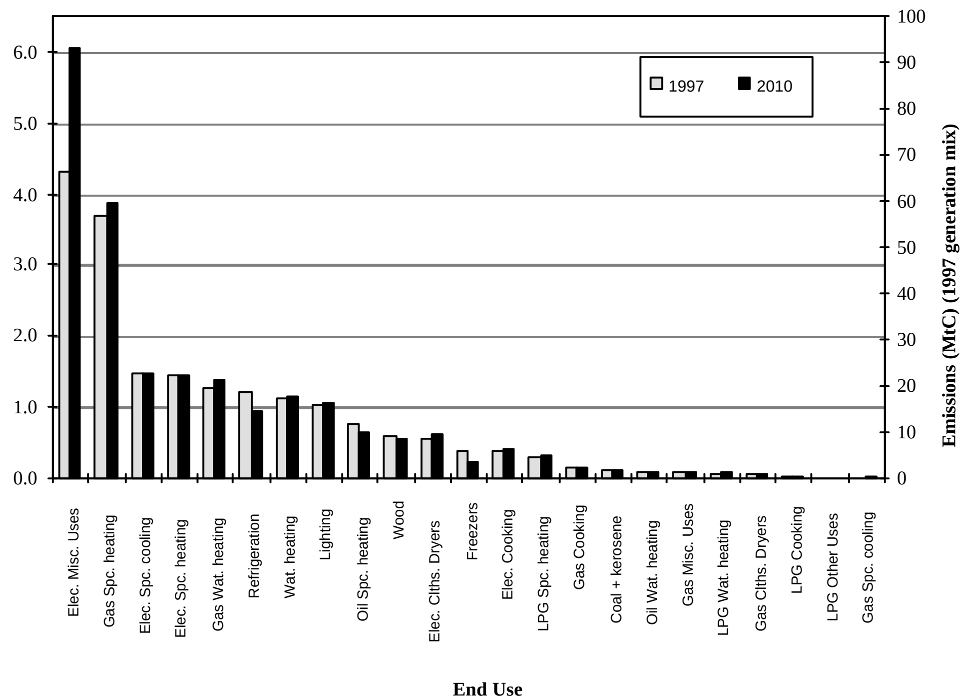
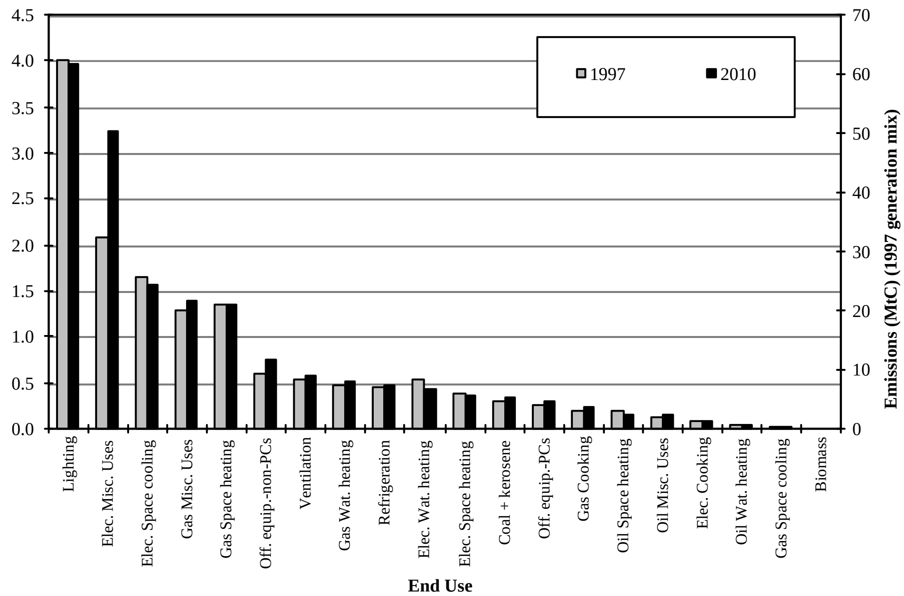


Figure 3.3 Commercial Sector Primary Energy Use and Carbon Emissions in 1997 and 2010 by End-Use for the Business-As-Usual Scenario



3.3.2 Maximum Cost-Effective Energy-Efficiency Potential

In determining the maximum cost-effective technical potential to be used as a baseline for development of the efficiency and high-efficiency/low-carbon scenarios, we reviewed and updated, as needed, the major recent sources of data on energy use and costs associated with upgrading to more efficient energy-using technologies. The results of this work, as well as the references on which it is based, are found in Appendix C-3. Once we determined the cost-effective energy-efficiency measures, we then used the energy use and incremental cost of new 1997 equipment for that end-use to calculate the potential efficiency improvement for that end-use. Table 3.4 lists the 1997 end-uses and their potential for energy intensity reductions when replaced by these highly energy-efficient technologies. As the table indicates, compared to 1997 new equipment, significant savings potential exists for many end-uses in the residential and commercial sectors.

The difference in energy demand between the maximum cost-effective case (100% of the potential) and the business-as-usual scenario for all buildings is 6.5 quads/year of primary energy in 2010. The efficiency and high-efficiency/low-carbon scenarios discussed below are based on the assumption that various shares of these savings are achieved.

Figures 3.4 and 3.5 show the percentage breakdown of savings for electricity and natural gas (these results are independent of the efficiency scenario because these scenarios vary only in the percentage of the maximum cost-effective resource assumed to be implemented, not in the character of that resource). More than 50% of the electricity savings is in “miscellaneous”, and about a quarter is in lighting, with the remaining quarter split between space conditioning, water heating, and refrigeration. About half of the natural gas savings is in residential space heating, with commercial space conditioning and water heating splitting the remainder about equally.

Figure 3.6 shows a conservation supply curve for electricity savings in the high-efficiency/low-carbon case. This graph shows the electricity savings by end-use associated with the cost of achieving those savings. On the x-axis are the projected savings in 2010 in TWh, and on the y-axis is the cost of conserved electricity (CCE) in cents/kWh (1995$). Total savings in this scenario are about 16% of baseline electricity use. The most cost-effective savings come from commercial lighting, which has a negative net CCE because of the labor savings associated with replacing incandescent A-lamps with longer-lived halogen IR and compact fluorescent lamps. The costs of savings in other end-uses range from 1.4 to 4.5 cents/kWh.

Table 3.4 Cost-Effective Energy Savings Potentials for Selected End-Uses in the Residential and Commercial Buildings Sector*

	Energy Savings
Residential	
Fuel Switching - clothes drying**	59%
Lighting	53%
Miscellaneous electric end-uses	33%
Fuel Switching - Cooking**	33%
Refrigeration	33%
Fuel Switching - water heating**	29%
Electric water heating	28%
Freezers	28%
Electric space heating***	25%
Gas and oil water heating	23%
Electric space cooling***	16%
Gas space heating***	11%
Gas and oil cooking	15%
Miscellaneous gas and oil uses	10%
Commercial	
Space heating (electric and gas & oil)	48%
Space cooling (electric and gas)	48%
Ventilation	48%
Miscellaneous electric end-uses	33%
Refrigeration	31%
Lighting	25%
Electric water heating	20%
Gas and oil water heating	10%
Miscellaneous gas and oil end-uses	10%

* Energy savings potentials are calculated as the percent difference in energy intensity of maximum cost-effective technology and new 1997 technology. Savings are achieved using technologies listed in Appendix C-3. It is important to note that the impact these potentials have on reducing energy demand in the efficiency and high-efficiency/low-carbon scenarios depends not only on savings potential but also on the magnitude of energy demand by the particular end-use (see Tables in Appendix C-2) and the rate of turnover of equipment for that end-use.

** Fuel switching energy savings potentials reflect the unit energy savings in switching from electric clothes dryers, ranges, and water heaters to gas. Electricity energy is calculated as source energy using conversion factors from the utility chapter.

*** Energy savings potential for residential space conditioning is greater with new shells than with retrofitted shells. Our estimates for electric space heating, electric space cooling, and gas space heating with new shells show additional incremental savings of 14%, 7%, and 8%, respectively, beyond savings achieved with retrofitted shells.

Figure 3.4 End-Use Electricity Savings, 2010

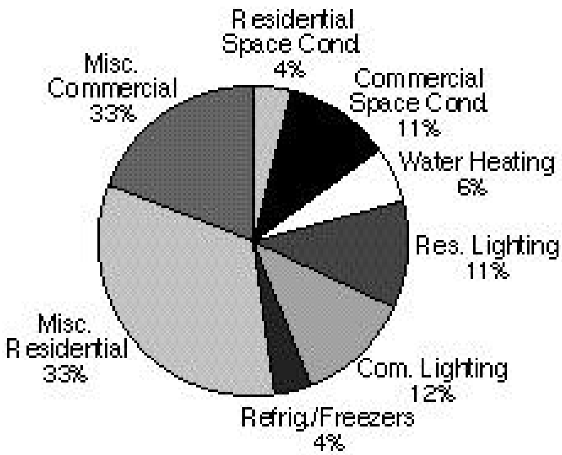
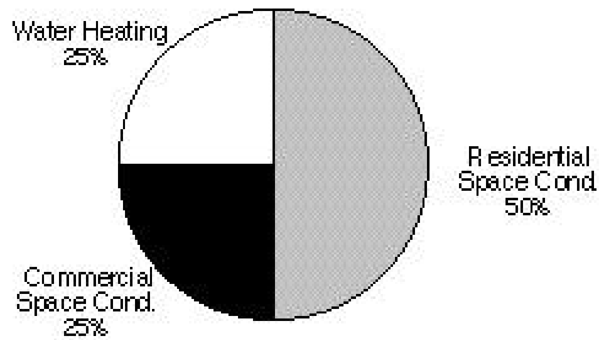


Figure 3.5 End-Use Natural Gas Savings, 2010



Note: The proportions of electricity and natural gas savings do not vary across scenarios. Total electricity savings in 2010 in the high-efficiency/low-carbon case are about 400 TWh, while total natural gas savings in this scenario are about 0.5 quads.

3.3.3 Efficiency Scenario Results

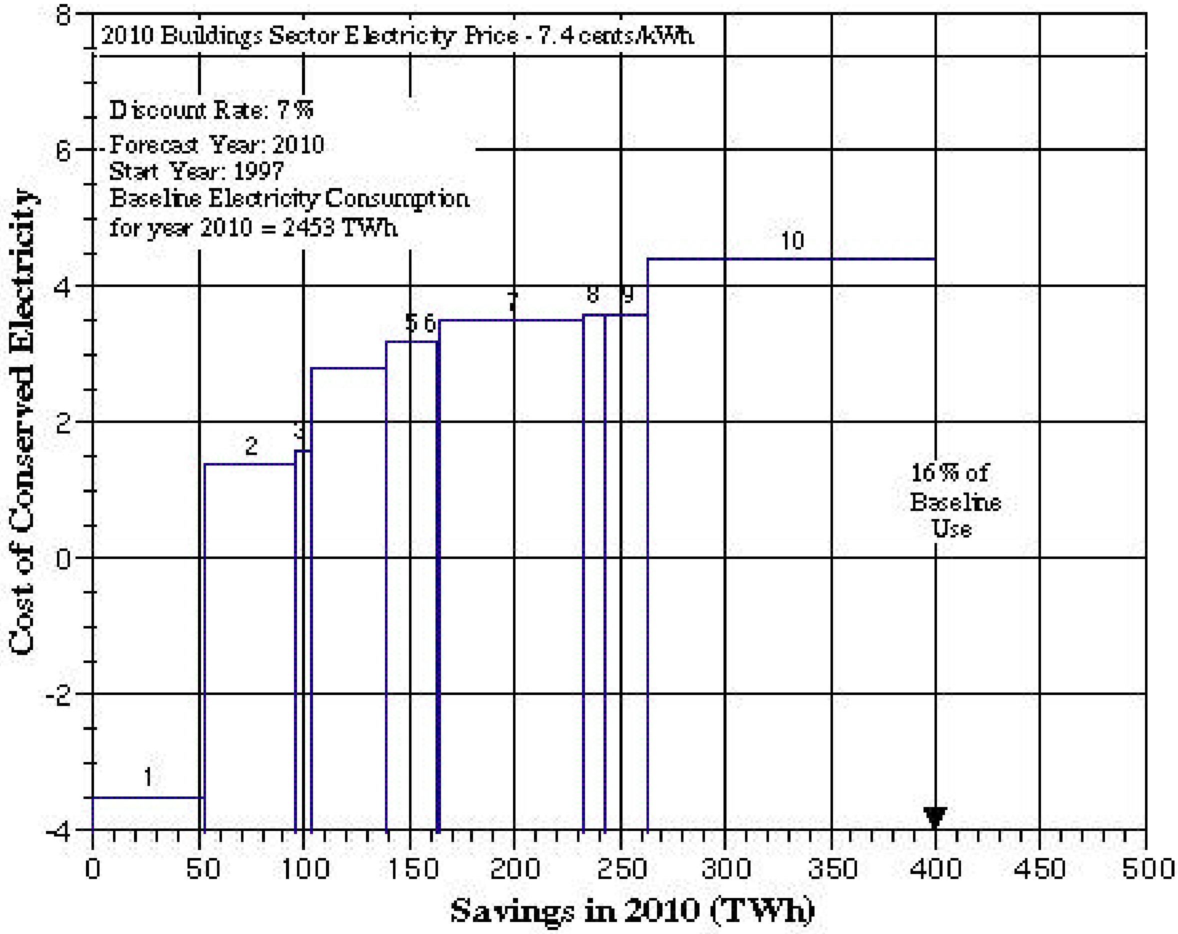
The efficiency scenario assumes that 35% of the maximum cost-effective efficiency savings are achieved by 2010. This assumption is based on expected savings resulting from a moderately vigorous effort to reduce energy use and carbon emissions using a combination of policy mechanisms that may include higher prices resulting from a cap and trade system, energy-efficiency standards, and information programs.

In the efficiency scenario, 2010 energy use drops to 34.1 quads while carbon emissions decline to 546 MtC. In this scenario, the total annual cost of energy services is $11 billion per year less than the annual energy services cost in the business-as-usual scenario, reflecting the fact that the decrease in energy expenditures resulting from more efficient technologies is greater than the increase in costs to purchase and install the technologies in residential and commercial buildings. The largest energy savings by end-use occur in miscellaneous electricity, lighting, water heating (residential) and space cooling (commercial).

3.3.4 High-Efficiency/Low-Carbon Scenario Results

The high-efficiency/low-carbon scenario assumes that 65% of the maximum cost-effective efficiency improvements are realized by 2010 as a result of a vigorous effort to reduce energy use and carbon emissions. In this scenario, 2010 energy use and carbon emissions drop further, to 31.6 quads and 512 MtC, respectively, at a total cost savings of $20 billion per year below the business-as-usual scenario. Annualized capital costs increase by $6 billion over the costs in the efficiency case, but annual additional bill savings are about $15 billion. Some of the carbon savings in the high efficiency/low-carbon case are associated with changes on the electricity supply side (see Chapter 6 for details).

Figure 3.6 Electricity Supply Curve By End-Use for Buildings in 2010, High-Efficiency/Low-Carbon Case



1 Commercial lighting
2 Commercial space conditioning
3 Commercial refrigeration
4 Residential lighting
5 Residential space conditioning
6 Commercial water heating
7 Commercial other uses
8 Residential refrigerators and freezers
9 Residential water heating
10 Residential other uses

Efficiency potential is calculated assuming 65% of technoeconomic potential is captured in the high-efficiency/low-carbon case. Savings from reflective roofing are contained in the residential and commercial space conditioning end-use categories.

Improving Efficiency and Saving Capital

Adding proven efficiency technologies to new homes can reduce monthly energy bills substantially. What is less well known is that clever design of new homes can also result in *capital cost credits* that can offset, in whole or in part, the additional capital costs of the more efficient technologies. For example, adding improved insulation and windows can allow a builder to reduce the size of the heating and cooling equipment and in some cases eliminate ductwork altogether. These credits can only be captured by builders who take a whole systems approach to design, but the benefits of such an approach are large, as shown by two real-world examples below.

Perry Bigelow, a builder in the Chicago area, has for years built highly energy-efficient homes that cost only \$300 to \$500 more to construct, in spite of his guarantee that these homes will have heating bills no higher than \$200 annually (Andrews 1994). He accomplishes this goal by creating a well-insulated building envelope with little air leakage (taking care to provide appropriate levels of ventilation) and by replacing the furnace with a high-efficiency water heater that also doubles as the space heater. By using hydronic heating, he can save \$1000 on ductwork. He also can downsize the air conditioner because the home's cooling load is so much lower than typical practice, saving another \$80 to \$100. These savings totally offset the cost of the added insulation and the air sealing, leaving a small additional cost to pay for low-emissivity gas filled windows and fluorescent lighting.

Builder Barbara Harwood, whose company is based in Carrollton, Texas, built a block of homes in Dallas called Esperanza Del Sol (Schwolsky 1997). The homes are small (1273 square feet) and inexpensive (\$80,000), but are so efficient that Harwood can guarantee that heating and cooling costs will be no more than \$1/day (\$365/year). She upgraded insulation levels, reduced air infiltration, and added an active ventilation system. To offset these costs, she used a smaller-capacity geothermal heat pump and redesigned the ductwork. With these offsetting cost credits, the more efficient homes cost only \$150 more than their inefficient counterparts, but save about \$40/month in energy bills. The consumer who purchases these homes would have to pay another \$1.10/month on an 8%, 30 year mortgage to finance the added capital cost; the monthly energy savings are almost 40 times larger, providing immediate positive cash flow to the homeowner.

These builders have discovered the benefits of an integrated design approach. They both use the "hook" of guaranteed maximum energy bills to market efficiency to customers who might otherwise be reluctant to spend more for it. They have shown that, with correct sizing of equipment and clever redesign of building systems, highly efficient homes need only cost a little more up-front.

Commercial buildings can also benefit from HVAC equipment downsizing. Pacific Gas and Electric Company's Advanced Customer Technology Test for maximum energy efficiency (ACT^2) had one pilot project in San Ramon, California (Houghton et al. 1992). This 20,000 square foot office building was retrofit using improved glazing, more efficient lighting, and better controlled HVAC systems. Chiller capacity was reduced by more than 40% because of better solar control from the windows and the reduced internal loads from lighting. The savings from the smaller chiller offset some of the cost of the window and lighting retrofits.

3.4 POTENTIAL FOR ADVANCED TECHNOLOGIES IN 2020[7]

To the casual observer, buildings in the year 2020 may look much like the buildings of today (Smith and Rivera, 1989). This is because Americans prefer familiar forms for their buildings and because new buildings amount to only 2-3% of the existing building stock in any given year. Nearly 90% of the residential buildings, and 80% of the commercial buildings, that existed in 1997 will still be occupied in 2010. By 2020, significantly more than half of the 1990 stock will still be in service.

However, beneath the surface, many significant changes are expected to occur that will affect how buildings are constructed, the materials and systems used to build them, and the way in which buildings are maintained and used (Smith and Rivera, 1989; Wendt, 1994). Without a sustained and vigorous public-private research, development, and demonstration (RD&D) partnership, these changes could lead to only modest improvements in energy efficiency. In contrast, an invigorated buildings RD&D scenario over the next 25 years offers the potential to produce breakthrough technologies that could dramatically reduce the energy requirements and environmental impacts of buildings, while enhancing affordability, long-term durability, resistance to disasters, and indoor environmental quality.

For advanced energy-efficiency technologies to penetrate the buildings industry by the year 2020, they will have to be cost-effective, and passing the cost-effectiveness hurdle will be challenged by energy prices that could decrease well into the 21st century. Thus, incorporation of additional features to make energy-efficient technologies more attractive to consumers will be needed to ensure success in the marketplace and should be part of the R&D planning process. RD&D will also be instrumental in capturing the potential of existing technologies by establishing better programming, design, and commissioning practices for buildings (Todesco 1996). Further, investments in training and education will be required to enable technicians and engineers to keep pace with a new generation of technologies and practices. New construction techniques, novel heating systems, electronic appliance tuning and control, more sophisticated building wiring practices, and the field installation of factory-built housing all require new talents for those who build, maintain, and service buildings. There must also be a concerted effort to facilitate the integration of new technologies.

This section identifies the potential improvements to energy-efficiency technologies that could result by 2020 given a sufficiently vigorous R&D effort. Savings discussed here would be in addition to savings estimated in the quantitative analysis for 2010 above.

3.4.1 New Technologies and Practices

Many of the changes in building technologies occurring over the next 25 years will be evolutionary in nature, resulting from ongoing research that is continuously providing solutions to such issues as moisture damage in structures, anomalous heat losses from envelopes, and indoor air quality problems. By 2020, these solutions will have evolved into cost-effective practices and products that will be the norm in new and existing buildings. In addition, a sustained, vigorous program of public and private-sector RD&D could produce many novel building technologies and practices by the year 2020. The following six areas offer great promise to significantly reduce the energy requirements of our nation's buildings through a combination of incremental and aggressive technology improvements:

- Advanced construction methods and materials;
- Environmental integration and adaptive envelopes;
- Multi-functional equipment and integrated system design;
- Advanced lighting systems;

• Controls, communications, and measurement; and

• Self-powered buildings.

In each area, thought must be given not only to energy-efficient technologies and energy costs, but also to the incorporation of other beneficial non-energy features that will accelerate their introduction into the marketplace, such as lower first costs, ease of integration, time savings, durability, comfort, and improved indoor environments.

3.4.1.1 Advanced Construction Methods and Materials

With sufficient RD&D support over the next 25 years, a systems engineering approach to the building's life-cycle (programming, design, construction, commissioning, financing, operation, renovation, reuse, and disposal) could become the norm. Such a transformation offers the potential to deliver buildings with lower total first costs and lower energy consumption, as well as higher overall quality and faster construction (Lawson, 1996; Lovins, 1992). The lower total first costs will permit the reinvestment of some capital savings into additional cost-effective, energy-efficient technologies. The total reduction in energy use could thereby be considerable.

By the year 2020, on-site labor for single-family homes, low-rise multi-family construction, and commercial buildings of standard design (e.g., franchise restaurants and retail stores) will consist primarily of assembling manufactured components and installing complete modules. This shift will require less skilled, and more semi-skilled, on-site labor. The expanded use of CAD/CAM technologies could enable "mass customization" capabilities, permitting the manufacture of virtually all residences and many commercial buildings. Quality and material improvements that are not affordable on a one-of-a-kind basis, can be assimilated into the high-volume manufacturing process. Continued research into the manufacture of building components is needed to enable these changes, to reduce waste, and to facilitate the recycling of unused materials.

Advanced modular construction methods will result in attractive, affordable, and flexible buildings that will permit longer occupancy in homes, offices, and other commercial buildings. Modular and easily installed heating, ventilating, and air-conditioning (HVAC) units with improved, leak-free, insulated ducting will reduce installation and operation costs. By extending the average length of stay in buildings, life-cycle costs become more important to decision makers. Durability and the need for reusable and recyclable materials will therefore increase in importance, generating the need for better durability testing tools and advances in materials, systems, and assemblies (Darrow, 1994). Better "engineered" wood, stress skin panels, optimized light-weight steel components, and adhesive assembly techniques will be needed. Greater use of recycled materials requires the development of higher "value added" uses for current wastes and the invention of low-value recycled products. Examples being developed today include the following: (1) mixed paper waste in lieu of pure newsprint to cellulose insulation and drywall; (2) wood wastes to engineered structural members as opposed to only particle board; (3) flyash to lightweight masonry products as opposed to site fill material; (4) corrugated paper to structural insulating panels; and (5) plastics to carpeting and wood/plastic composites. The recycled materials must also be low- or non-emitting materials in order to meet consumer concerns about indoor air quality. A program of vigorous materials research could make these new materials commonplace by 2020.

By 2020, building life-cycle information management systems will create efficiency in the architectural/engineering/construction process and in building operations. Information systems will facilitate communication of programming and design intent through construction, commissioning, maintenance, and operation of buildings. Performance tracking will insure persistence of savings from efficient design and equipment. And, most significantly, continuous improvement in buildings will occur through feedback of performance information to design of new buildings and renovations.

Over the next quarter century, there will be greater use of computer software in every aspect of the building life-cycle. Design tools and building simulators will be more powerful and easier to use, with improved graphical interfaces and links to manufacturer databases of equipment specifications. There will be construction management and commissioning software for use in all stages of a building's life-cycle including early design and commissioning. This software will be used to create calibrated computer models to verify that actual building performance meets pre-specified design targets that could be part of a performance contract. The calibrated model could have many uses in operations and maintenance, including assisting in evaluation of the least-cost energy supplies, optimization of existing control strategies, and analysis of possible retrofit options. Finally, such data on actual as-operated conditions close the feedback loop that is problematic today. Building designers will finally have an opportunity to learn how buildings they design actually perform, and their future designs will benefit from lessons they learn based on existing buildings.

3.4.1.2 Environmental Integration and Adaptive Envelopes

Advanced designs and technologies that intelligently integrate the performance of buildings with the outdoor environment offer the potential to more efficiently heat, cool, insulate, ventilate, and illuminate interior spaces. A variety of building designs tailored to the wide range of climates in the U.S. will reduce first costs and operating costs. Equipped with these climate-specific and smart technologies, the word "shelter" will no longer imply the exclusion of outdoor elements; instead it will refer to structures that capitalize on fluctuating outside conditions to create interior comfort and light.

One of the most significant changes in envelope performance from 1970 to 1995 was the development of a new generation of window technology that involved high-transmittance low-emissivity (low-E) glazings; the introduction of this new window technology resulted in a major shift in the window marketplace. By 2020, the market penetration of such technologies could double as high-rate, thin-film coating techniques make it possible to coat glass and plastic for cost-effective use in virtually every climate. New types of highly insulating glazings (such as aerogel and honeycomb) will compete for new markets if materials research is able to produce a window that, by enabling the diffuse solar gain to exceed the winter thermal losses, outperforms a highly insulated wall even on northern exposures in winter.

In most larger commercial buildings and in sunbelt housing, control of solar gain is critical. Since building needs vary widely and climatic variables are unpredictable, one ideal component would be a dynamically controllable "smart glass". The fundamental materials science technology base for "active" and "passive" smart glazing technologies such as electrochromic coatings was developed in the 1990s. However, RD&D resources are needed to develop viable and cost-effective materials with optical properties that can be switched passively. In addition, research on switching mechanisms is needed to assess the potential applicability of the range of alternatives, including short wavelength switching to a reflective mode and long wavelength switching for thermal comfort (Kammerud, 1995).[9]

To date, research on insulation has focused on static insulation systems, where insulation is simply put in place to increase the thermal resistance of the roof, wall, or floor by a fixed amount. An alternative is to consider dynamic systems, in which the performance of the building envelope changes with the environment to minimize the building energy load. One study (Fine and McElroy 1989) found that dynamic building envelope systems (insulation, roofs, walls, and windows) could reduce heating and cooling loads by 20 to 35%. Adaptive envelopes should be developed which integrate other useful features, such as ventilation air intakes with heat exchangers and sensors that are engineered as an integral part of the envelope, or energy-efficient windows as part of a unit.

Better use of thermal storage concepts would increase the ability of passive solar heating and cooling to offset the use of mechanical systems. One possibility is to distribute natural heating and cooling more uniformly over the day with resultant decreases in both heating and cooling requirements. Development of phase-change materials with storage capacity and release rates adapted to building use is needed. Applied R&D is needed to make such materials economically competitive with standard building products, and to demonstrate their durability and safety. In addition, to achieve the technical potential of these thermal mass strategies, design and construction guidance is needed to identify how mass and insulation should be rearranged to optimize thermal storage effects in specific climate regions (Christian, 1991).

Self-drying roof concepts are under development, and their commercialization offers significant cost and energy benefits. Behind this work is the notion that roofs should be designed to accommodate occasional leaks; that is, there should be a means to dry out the roof and restore it to its original thermal performance after a leak is patched. One promising technique is to design roofs that dry to the interior through evaporation. By extending roof life, self-drying promotes the installation of better insulation, since the originally installed insulation will remain in place longer. In addition to reducing energy loss, self-drying roofs also significantly reduce the cost of repairing, replacing, and disposing of roofs.

The success of environmentally adaptive envelopes depends upon improved design and commissioning practice, the development of advanced manufacturing techniques, new materials, and sensor and control technologies to produce customized wall, roof, and floor panels that meet the needs of buildings in different climates. Other important properties and features should be simultaneously sought in the development of new materials such as reduced maintenance, resistance to water condensation, and low emissions. Research is also needed to integrate the dynamics of such advanced envelopes into total building energy management systems.

Mitigating Urban Heat Islands With Cool Roofs And Trees

The benefits of reducing urban heat islands through reflective roofing, white pavements, and tree planting have gained increasing attention in recent years (Rosenfeld et al. 1996 and 1997, Konopacki et al. 1997). These savings are both from the direct effect of sunlight being reflected (by white roofs) or blocked (by trees) and hence prevented from entering the building envelope, and from the indirect effect of cooler ambient conditions brought about by evapotranspiration from trees and increased albedo. The cooler ambient conditions have the additional benefit of reducing smog formation (which is directly related to air temperature).

The calculations above include estimates of savings from the direct and indirect effects of cool roofing on building energy use but do not include the potential effects of large-scale tree planting. In the efficiency case in 2010, cool roofs save about 4 TWh of cooling electricity, while increasing heating gas use by 0.01 quads. In the high-efficiency/low-carbon case in 2010, cool roofs save about 8 TWh of cooling electricity (worth more than $500 million per year), while increasing heating gas use by 0.02 quads (worth more than $100 million per year). The associated net carbon savings (after subtracting out the penalty for the increased heating gas use) are 0.2 MtC in the efficiency case and 1.3 MtC in the high-efficiency/low-carbon case. The cost of these reductions are negligible, because changing roofing materials to be more reflective at the manufacturing stage is generally a zero cost option. The development of advanced roofing, paving, and coating technologies would improve the longevity and economics of these cool community options.

The additional savings from tree planting have not been included in the calculations, but the direct and indirect effects from trees are generally of the same order of magnitude as for cool roofs (Rosenfeld et al. 1996). The total savings from cool roofs and trees together would therefore be on the order of 2-3 MtC in the high-efficiency/low-carbon case by 2010.

The cost of tree planting is more difficult to estimate, because of the sizeable unquantifiable benefits of trees, as well as the long-term maintenance costs. Most people regard trees as a net positive contribution to their local environment, and it is likely that the overall benefits (including the energy and carbon savings benefits) substantially exceed the costs, but because of the uncertainties in estimating these costs, we did not include tree planting in our savings estimates.

3.4.1.3 Multi-Functional Equipment and Integrated System Design

During the period through 2010, the efficiencies of HVAC equipment, water heating and other appliances will continue to increase through incremental improvements. Efficiency improvements will probably continue to be driven both by minimum efficiency standards as well as by marketplace competition for technologies that have low operating costs because they are efficient. In many cases, however, appliance and equipment efficiencies are reaching either their thermodynamic limits, or can be made higher only at significantly higher first cost.[10] For example, electric resistance water heaters have become more than 90% efficient with 100% as the maximum. Gas water heaters and refrigerators provide other examples where efficiencies may be reaching either an economic or thermal limit. Condensing gas water heaters that have efficiencies above 90% have been developed, but are generally too expensive for a mass market. In the case of refrigerators, applied research and development has recently produced a 20 cubic foot refrigerator which consumes no more electricity than a 40-watt light bulb running continuously (350 kWh/year). We anticipate that the technologies used to reach this performance level will be available to the U.S. refrigerator market in the next decade. To move refrigerators, as single-function appliances, beyond this level of performance does not appear to be cost-effective in the near-term or beyond if real energy prices continue to decrease.

Opportunities continue to exist for reducing losses in poorly designed hot water storage and distribution systems. Improved tank/flue designs, improved piping layout and design, and advanced circulation systems are some of the possibilities.

Based on the limits to performance for single-function equipment such as refrigerators, water heaters, and HVAC equipment, RD&D efforts need to focus on multi-functional equipment and appliances to provide the next quantum jump in efficiency improvement. Multi-functional equipment needs to be developed that combines and integrates the functions of several appliances into a single, highly efficient device. Such equipment promises to be highly efficient because the heating and cooling that is rejected by a single-function device can be put to use in the integrated appliance, and the component with the highest efficiency can be used to provide a dual function.

An example of multi-functional equipment is an integrated water heating/space conditioning system which uses heat pumping to meet space heating, air conditioning, and water heating loads. As a combined, integrated appliance, this unit's efficiency (as measured by the Seasonal Energy Efficiency Ratio, or SEER) could be a full 70% higher than the combined efficiency of today's central air-conditioning system and water heating system. Energy-efficient air filtration, as well as humidity and temperature control, could be incorporated into HVAC systems to reduce indoor concentrations of airborne particles such as pollen, other allergens, and infectious agents that cause adverse health effects. This type of integrated technology can be applied to residential as well as commercial buildings. As the efficiency of a single-function device is improved through incremental development, as part of an integrated approach, this device is able to provide still higher efficiencies.

There is also a large opportunity for integrated products that can control space humidity and temperature independent of each other. Research on combined systems that use desiccants to control humidity and vapor compression air conditioning to control temperature is expected to result in an efficient, integrated system that can provide better comfort at reduced operating costs.

Further opportunities exist for improving the efficiency of heating and cooling systems in buildings through integrated systems design, right sizing, modular/multiple equipment configurations, and better integration of the process for distributing space heating and cooling within buildings (Shepard 1995). As air conditioning and chiller efficiencies continue to improve with cascade, multi-stage, and turbine-assisted compressors, the energy consumption and electrical demand associated with oversizing, poor part-load performance, and the distribution of air and water becomes a greater fraction of the total HVAC energy use in both residential and commercial buildings. Research on load diversity, system integration, and design paradigms can reduce both peak demand and energy use. In addition, research on advanced thermal distribution technologies could enable the development and commercialization of higher-efficiency, quieter thermal distribution systems, with air filtration to improve indoor air quality. At a higher level, integrating heating/cooling devices as part of the distribution system itself, along with improved integration of task/local environmental control systems, would provide efficiency benefits and enable use of control technologies to target heating and cooling within a building.

There are other options for appliance integration, including combining water heating with dehumidification, mechanical ventilation, and/or refrigeration. In these cases, heating or cooling is produced for multiple applications and at much higher efficiency than would otherwise be possible. In the 2000 - 2010 time period, research in fields of heat transfer, controls, component technology development, and systems analysis will need to be conducted so that industry can take these results and apply them to developing integrated products for both residential and commercial buildings. By 2020, we anticipate that efficient integrated and multi-function products could capture a substantial fraction of the U.S. market for space conditioning, ventilation, water heating, and refrigeration.

3.4.1.4 Advanced Lighting Systems

Lighting is a dominant energy end-use in the commercial sector, an important use in houses, and an essential element of roadway and outdoor use. At the national level, lighting accounts for 23% of all U.S. electrical energy use. Through the development and intelligent use of more efficient lighting technologies and design, lighting energy use could be reduced by over 50% by 2020 with equal or improved health, comfort and productivity.

Lighting use is characterized by a tremendous diversity of applications and needs, and an equivalent diversity of sources, fixtures, controls, and designs. Thus, energy efficiency can best be achieved by an array of new and existing technologies intelligently matched to the appropriate lighting needs. Unlike other aspects of the building infrastructure, most lighting system components are replaced at a relatively high turnover rate within ten years, and thus provide opportunities to introduce more efficient technologies on a regular basis. At the national scale, we spend $10 billion/year for new lighting equipment but $40 billion/year for lighting energy consumption. By 2020, we must make a transition to investing more each year in improved technology with the benefit of dropping the annual consumption figure by 50%.

Changing the overall efficiency of U. S. lighting use can be viewed as improving four efficiency parameters: (1) lamp or ballast efficacy, (2) fixture efficiency, (3) spatial task efficiency, and (4) temporal control efficiency. There are large opportunities for improvements in each of these areas:

Lamp efficacies for fluorescent and other gas discharge sources have improved modestly over the last 20 years, but are still well below the theoretical limit. The industry is exploring new electrodeless solutions in both small sizes (10-100 watts) and in the kilowatt range. Large lamps, such as the sulfur lamp, have demonstrated higher performance in prototype form. Some technologies have other advantages, such as reduced maintenance due to long operating life, or better environmental properties (e.g., mercury-free lamps). Most of the new discharge sources will benefit from continued development of less expensive, smaller, and more efficient electronic power supplies. Dimmability will also be more readily achievable using these new power supplies. Light sources that use phosphors may be further improved by advances in the chemistry of phosphors.

By 2020, there will be many new CFL options with smaller size, better color rendition, higher luminous output, and dimmability. But there will still be a tremendous market need for a long life, very low cost, incandescent lamp replacement, perhaps utilizing improved filament technology or halogen lamps with IR reflecting coatings. Finally, there are other contenders for the small source market such as mini-HID sources and solid state light sources (LEDs or laser diodes).

There will be continued improvement in fixture design for both direct and indirect lighting systems so that a greater fraction of the light is usefully extracted from the source, using innovations in highly reflecting surfaces, refractive and diffracting materials, and non-imaging optical designs. Two seemingly contradictory trends will continue through 2020. One trend will be towards localized lighting that provides just the lighting needed at each task location and is flexible enough to adapt to the ever-changing needs of today’s office and factory environments. The other trend is towards the use of centralized lighting in situations that require uniform light levels on a fixed schedule over long periods of time. Hollow light guides and light pipes must be developed to meet these needs and fiber optic designs can be used for smaller-scale centralized solutions.

Lighting controls have only recently advanced beyond simple on-off, multi-level, or time clock controls to occupancy-based controls and photosensor controls that respond to daylight and lumen maintenance. By 2020, new generations of smart control systems will respond automatically to changing task and environmental needs. Voice-activated controls and flexible linkages (wired and wireless) between light sources and tasks will provide new flexibility in both office and retail environments. Controls linked to dimmable lighting systems and to building energy management control systems (EMCS) will provide an equivalent spinning reserve load that can be used by owners when negotiating utility contracts with electricity suppliers in the deregulated environment of 2020.

Some of the most important issues in the lighting community today are related to the human dimension of occupant response to the indoor luminous environment. Lighting design has a direct impact on performance, health, and satisfaction in the built environment; however, the nature of that impact remains elusive. By 2020, the challenge is to conduct the research studies that will establish definitive causal linkages between design parameters and occupant impacts, and then apply these conclusions to the development of new technology and designs.

With only a modest RD&D effort, incrementally more efficient lighting components, including improved bulbs, fixtures, and controls, will be in use throughout all building types in 2020. Important improvements in lighting performance will result from using advanced techniques to improve the performance of fluorescent lamps and expanded use of diodes as light sources. Systems will be available to permit the integration of very-high efficiency lighting such as the sulfur lamp into common interior spaces.

A more vigorous program of lighting research could ensure that, by 2020, the nation will be discovering the virtues of lighting systems that deploy a mixture of centralized, energy-efficient, artificial light sources, tracking sunlight concentrators, and light distribution systems for buildings with high lighting usage. Offices and retail stores that require high lighting levels would be ideal candidates to field test such systems. A few, high-intensity, super-efficient light sources, centrally located, could then replace the numerous distributed light bulbs currently used. Whenever local climatic conditions permit, the sun could provide the light source in lieu of artificial sources. This piped lighting system could enhance many daylighting strategies based solely on architectural design elements. These piped systems, which use sunlight supplemented by super-efficient artificial light sources, could cut lighting-related power consumption in office buildings dramatically, since sunlight is usually available during normal office working hours. In addition to significant reduction in energy consumption for lighting, this system offers the potential to dramatically reduce lighting maintenance costs by using fewer artificial light sources and for much shorter periods.

Development of such lighting systems will require scientific breakthroughs and technical expertise in advanced artificial light sources, optical systems design, materials development, thin film coatings technology, fiber optics, photonics, manufacturing technology, systems engineering and modeling, instrumentation and controls, and human factors.

3.4.1.5 Controls, Communications, and Measurement

Computer technology has made possible a revolution in equipment and capabilities for electronic control of devices in homes, offices, and industry over the past 20 years. Similarly, significant advances in communications and information capability have introduced major changes in life styles and work practices over this same period. Over the next twenty years, this trend is expected to continue, offering additional opportunities to increase the efficient use of energy in buildings. The increasingly deregulated and converging energy and communications industries will play a major role in defining, commercializing, packaging, and delivering these new energy services and technologies to building owners. The fact that deregulation has resulted in greatly reduced RD&D investments by utilities underscores the need for a sustained, vigorous public-private partnership to ensure that energy-efficiency innovations emerge.

The communications industry has adopted programs for universal hardware and software connections between most functional components. The controls industry has initiated similar measures (*ASHRAE Journal*, November 1996, p.36). When universality is achieved, systems designers can begin to lay out and wire buildings with centrally located communications/control centers for all buildings including homes. This affords the opportunity to significantly reduce power requirements by eliminating full replication at each building station. That is, there needs to be only one video/audio receiver with low-power monitors at other sites, one computer central processing unit with low-power (e.g., liquid crystal) terminals where needed, one energy management control system (EMCS) with zone controllers where needed, and so on.

Developing and incorporating increased intelligence directed at energy use and control diagnostics in future generations of EMCS will allow these devices to maintain higher quality building environments with less expenditure of energy. Expected advances include EMCS with performance evaluation and equipment status tracking ability, as well as predictive capabilities. For example, EMCS with more powerful computational capability and with more sophisticated mathematical modeling can couple weather predictions with building response characteristics and occupancy, light, and moisture sensors to predict building performance and more closely match supply and demand of HVAC and lighting. Energy management and control systems may also be developed to enable the selection of least-cost energy service providers and rates (see further discussion under "Self-Powered Buildings" below).

Future EMCS will utilize networks like the Internet to transmit data, sound, and video for real-time remote analysis. This will permit integrated buildings service providers to track the performance of heating and cooling plants, diagnose failures, test machinery, and to communicate findings to building owners and operators, all without setting foot in the building. Some "full service" providers would also offer other services including energy management, security, and property and facilities management.

For appliances such as clothes washers and dryers, control and communications capabilities will allow for remote programming and cycle control as needed. Delayed start, checking on cycle progress from a remote location, and modification of settings remotely are all examples of potential capabilities. Additional research to develop more sophisticated sensors and control logic will increase future ability to measure and control energy use in the ever-widening pool of appliances and equipment used in buildings. Advanced sensors can check the status of food being cooked, room lighting levels, and thermal comfort and instruct controllers to automatically adjust appliances for optimum operation.

The development of advanced sensors, controls, and communications equipment needs to reflect the nature of changing "plug load" devices in buildings. The forecasted rapid growth in miscellaneous electricity consumption in buildings suggests an important future role for a broad range of novel control strategies to promote energy efficiency. In addition, advances in office equipment performance could mitigate potential increases in these miscellaneous electricity uses in many parts of the commercial sector (Komor 1996).

3.4.1.6 Self-Powered Buildings

The move toward a competitive marketplace for energy services such as gas and electricity will be essentially complete by 2010. By 2020, that market will have matured to accommodate complex buy-sell utility service arrangements monitored and administered by automated systems. This, combined with the advent of power production and improved energy storage technologies, will give building owners new levels of flexibility in meeting their energy requirements, as well as the possibility of revenue streams from the sale of energy or ancillary services. Buildings will cease to be simply consumers of electric utility services but may supply all or a portion of their own energy requirements or, if the economics are right, sell to others. Removal of utility and environmental regulatory barriers would also accelerate the adoption of combined heat and power systems.

Small turbines running on natural gas are likely to be the first step in this process. These will allow buildings to generate their own electricity, with the reject heat from the turbines being used for domestic hot water or building space conditioning. Six manufacturers have announced actual or planned availability of gas turbine electric generators in the 50 kW range. Costs are uncertain, but will likely mature in the $750-$1000/kW range, including heat recovery equipment. Barriers to implementation include mechanical maintenance requirements as well as cost. The advent of automated control and diagnostic systems will make these distributed power plants as “forgettable” as any other piece of space conditioning equipment.

The next step in the development of the self-powered building will be the advent of low-cost fuel cells. The fuel cell is a unique technology that can revolutionize the way building power, heating, cooling, and water heating are generated and maintained.

Potential Additional Savings From Advanced Fuel Cell Technologies

In the high-efficiency/low-carbon scenario, fuel cell technology is also likely to make a contribution to reducing carbon emissions by 2010. While we have not included fuel cells in our main building sector scenarios, we examined recent technology projections from Arthur D. Little (ADL) and estimated the potential carbon savings from fuel cells in our high-efficiency/low-carbon case.

There are several different fuel cell technologies under development, including the phosphoric acid fuel cell (PAFC), the proton exchange membrane fuel cell (PEMFC), the molton carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). In addition, there are advanced gas turbines under development that could supply the same services as fuel cells, for comparable costs. We do not address the exact mix of technologies that might deliver carbon savings by 2010, but calculate the potential impacts assuming that some combination of these technologies would contribute savings.

Arthur D. Little created what they termed an "optimistic" scenario that resulted in 8200 MW of installed fuel cell capacity in commercial buildings by 2010. This estimate assumes a $50/tonne carbon charge and an aggressive commitment to building sector fuel cell development at or above current levels of funding. Their results imply that about 5% of all commercial building floor area in 2010 will have heat and power supplied by fuel cells.

Such penetration of a new and untried technology is ambitious by any measure. Because we are interested in a "best estimate", not an optimistic scenario, we chose to reduce the expected penetration to 65% of ADL's forecasted levels for our high-efficiency/low-carbon case (4.9 GW). For our more cautious case, we reduced the penetration again to 35% of ADL's forecasted levels (2.45 GW). As described in Table C-2.9 in Appendix C-2, implementation of this technology (or some combination of fuel cells and small advanced gas turbines in buildings) at the efficiency case level would result in primary energy savings beyond the high-efficiency/low-carbon scenario of about 0.14 quads, and additional carbon savings of about 2.5 MtC. The savings in the cautious case would be about half of the efficiency case savings. (See also Appendix D-3, in which the technical potential for commercial-sector advanced turbine systems in the 5-15 MW size range is estimated to be about 12 GW in 2010 at an estimated cost of $350/kW.)

To date, no other system identified provides all the benefits of the fuel cell. The fuel cell can generate electricity, provide heat and hot water, offer fuel flexibility, and operate quietly; in addition, the fuel cell is modular, is a non-polluter, and has an overall conversion efficiency potential of 80% or better (Fiskum, 1997). Unlike gas turbines, fuel cells have no moving parts and are therefore inherently quiet. The ability to tailor the installation to the thermal needs of the building by selection of fuel cell technology will also be attractive. For example, proton exchange membrane (PEM) fuel cells, whose operating temperature does not exceed 100 degrees Centigrade, will be used in installations with only low-level waste-heat applications such as domestic water heating. Other types, such as molten carbonate and solid oxide fuel cells, operate at higher temperatures for applications requiring a higher quality heat resource.

Fuel cell prices currently range from $3000/kW to $5000/kW for commercially available phosphoric acid and near-term PEM cells, respectively. An aggressive RD&D program could cut these costs in half in less than ten years. Research needs include work on high-risk components and processes, including heat exchanger development to bring the high-temperature hydrogen stream in line with PEM cell stack temperature, and catalyst development to increase CO tolerance and to mitigate carbon monoxide contamination degradation of the catalyst (Fiskum, 1997).

Another key component of the self-powered building will be building-integrated photovoltaic (PV) panels, an application which will become more widespread as the costs of PV cells decline. Full implementation of this concept will require storage to achieve full flexibility, and such systems could include compact, high-efficiency flywheels as a means of taking advantage of the diversity between load and resource peaks. In some applications, notably commercial buildings located in high solar resource areas, the coincidence between the mid-afternoon resource peak and the demand for such services as air conditioning may minimize the need for storage. In any case, the availability of an electric power spot market, accessed by the building's automated energy management computer, will allow real time purchases of power when needed or sales of excess power when available. PV system costs are still in the range of $7000/kW without storage, but improvements in solar cell manufacturing processes and inverter technologies support program goals calling for reductions of more than 50% in ten years or less.

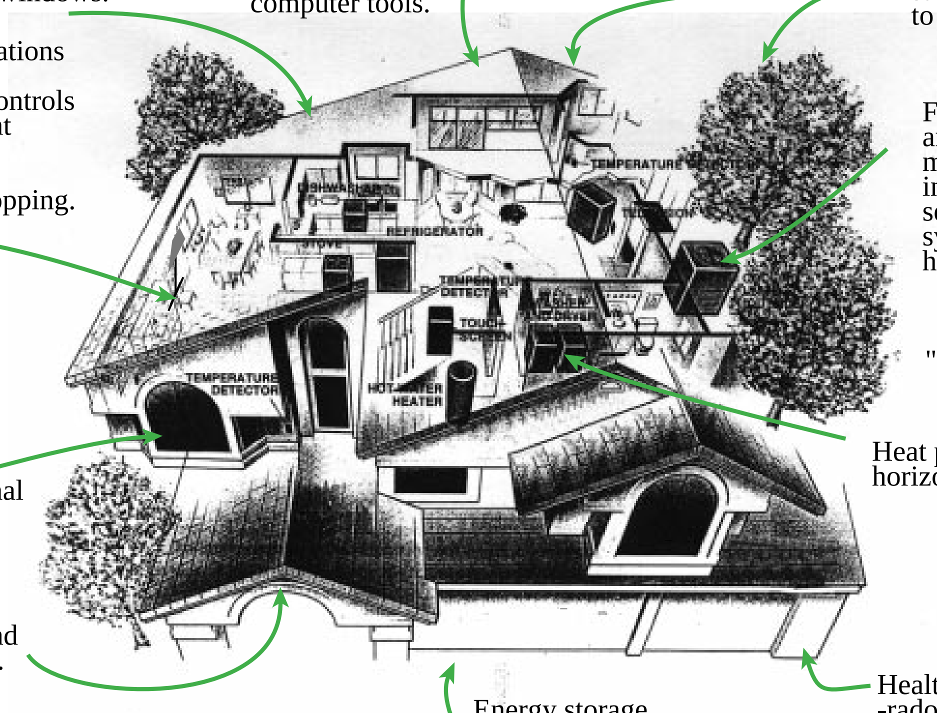
3.4.2 Best Practice Buildings in the Year 2020

3.4.2.1 "Best Practice" Housing in 2020

By the year 2020, a vigorous RD&D program could produce many advanced technologies that together will greatly reduce the average annual energy budgets of American families. The "Best Practice" home of the year 2020 is defined as a home that employs those energy technologies that are predicted to have the lowest life-cycle costs when purchased in the year 2020, under the assumption that a "high-efficiency/low-carbon" scenario unfolds between now and then. A collage of these best practice features is shown in Figure 3.7.

The best practice home in the year 2020 will be factory built and shipped to its site as modules or subassemblies. The use of integrated systems design and CAD/CAM technologies for "mass customization" will have produced these components and modules to reflect the particular requirements of the home buyer. On-site construction work will consist primarily of assembling these manufactured components and modules, rather than fabrication from raw materials.

Figure 3.7 Best Practice Home of the Year 2020



The best practice home will use affordable, modular, and therefore flexible techniques to permit longer occupancy. Durability and quality of the basic structure will significantly improve over the year 1997, and adaptive envelopes will provide significant energy advantages. Material consumption in residential structures will be reduced through the use of recycled materials and engineering advances in materials, systems, and assemblies which provide stronger, more durable, lighter, and less expensive structures. HVAC systems will be right-sized and refined to match reduced cooling and heating loads and improved comfort features of the envelope. Thermal distribution systems will effectively transport heating and cooling to the conditioned space. Climate-appropriate advanced ventilation strategies will range from passive ventilation systems to filtered systems to heat exchange systems.

Thermal mass will be strategically used to improve comfort and efficiency. “Smart” windows will see widespread use in upscale houses and for specific rooms and orientations in general housing. When properly linked via controls and sensors to HVAC systems, improved comfort can be provided with downsized systems.

Widespread use of paneling and shingles with built-in PV arrays, fuel cells, and advanced energy storage systems will significantly reduce overall building sector non-renewable energy needs and will either deliver electricity back to the grid or will provide energy for family electric vehicles. Building-integrated photovoltaics will be widely employed in new home construction, and a strong retrofit market for PV shingles will have developed as well.

Advanced high-efficiency lighting systems actively operating with an array of daylighting and site/task strategies will optimize building luminosity and reduce energy consumption. Appliances, lighting, and building control systems will all incorporate smart technology to closely match energy and water supply and ambient conditions with need. The best practice home in 2020 will be low in volatile organic pollutants due to the use of low-emitting building materials, and will be equipped with sensor-controlled energy-efficient ventilation and air cleaning to provide good air quality. Automatic load modulation of heating and cooling systems in response to varying weather, environment, and occupant demands will be installed in best practice residences. In addition to improved sensors and controls, zoning and variable loading of the heating and cooling system will be used.

The home may have a new generation of high-efficiency gas appliances operating much closer to combustion temperatures, or it may be equipped with an integrated water heating/space conditioning electric heat pump system that minimizes waste heat. These multi-functional systems will focus on occupant thermal comfort rather than conditioning the space.

Distributed water heating capability (i.e., instant heating at the faucet) may provide supplemental "on-demand" water heating. Water use and energy efficiency will also be enhanced by improved design and technology for distribution systems. In addition, a greywater irrigation system equipped for sterilization of effluent may reduce the water required for landscaping, gardens, and lawns in arid or water-constrained regions of the country.

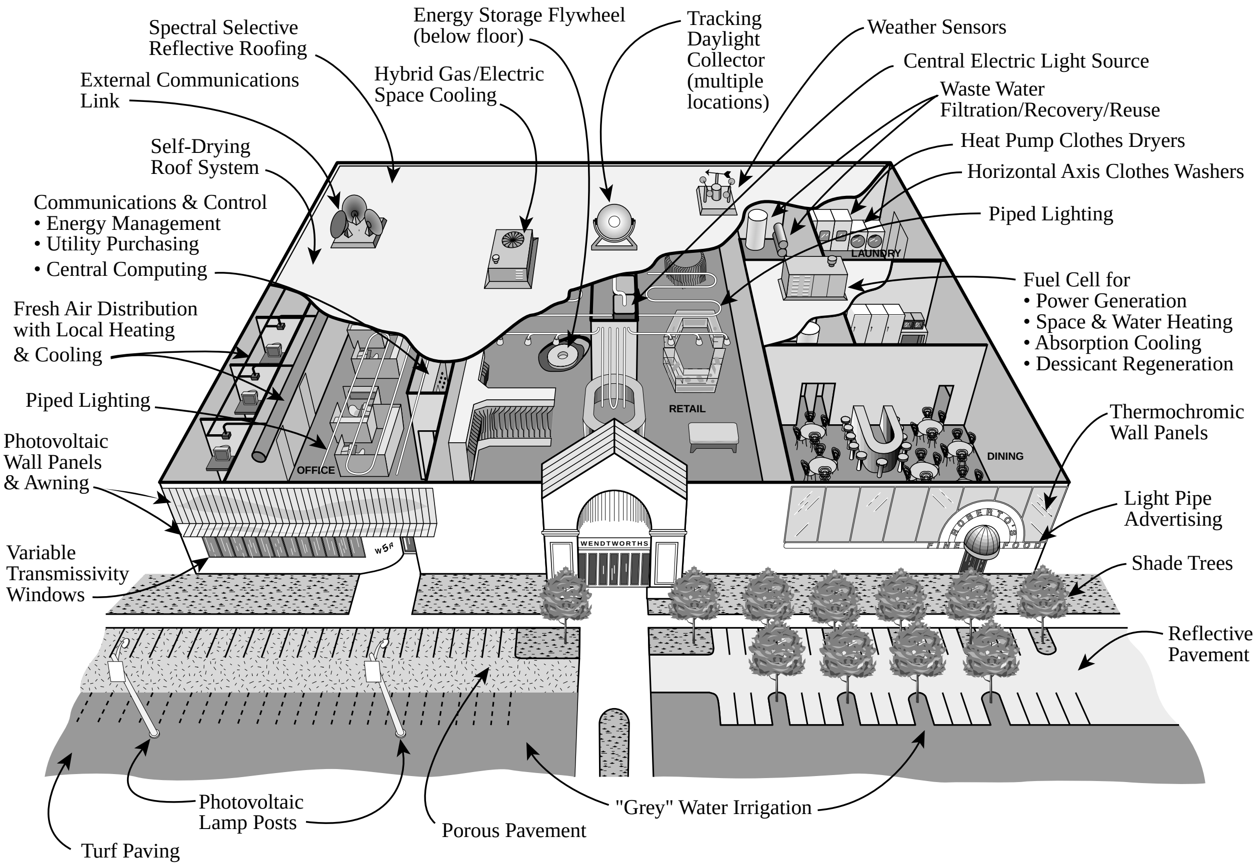
Home computers and sophisticated communication systems will begin to permit the use of the home as the location of office, secondary school, routine medical treatment, and selected shopping activities. This will begin to change the "mix" of building types as well as the need to commute to these activities.

3.4.2.2 “Best Practice” Commercial Buildings in 2020

By the year 2020, “best practice” commercial buildings will have many advanced technologies that will greatly reduce the cost of their utility requirements. More advanced programming, design, construction and commissioning processes will enable both reduced first costs and reduced operating costs. Varying designs will match building systems with the wide range of climate conditions found in the U.S. Commercial buildings will be designed and constructed to provide indoor environments that increase the productivity of workers. A collection of alternative technologies and options that could be cost-effective in the year 2020 – under the high-efficiency/low-carbon scenario – are illustrated in Figure 3.8. The drawing shows a composite commercial building containing retail, office, laundry, and dining facilities.

Commercial buildings will continue to look similar to those existing today. The primary change will be in the "mix" of these facilities as the advances in electronic information dissemination reduce the need for physical interaction, and therefore the size, of some commercial buildings. Some "traditional" commercial buildings, involved primarily in the transfer of information and knowledge (e.g., offices and libraries) will be significantly down-sized as their physical interaction (people-related) activities are replaced with electronic communication capabilities. Improved communications (combined with just-in-time inventory control) will also permit the reduction or elimination of many stock rooms as well as warehousing and distribution facilities. Many commodities will flow directly from production to end-use.

Figure 3.8 Best Practice Composite Commercial Building of the Year 2020



The state-of-the-practice commercial buildings will rely heavily on manufactured components for their construction. One-of-a-kind structures may continue to have many site-built components, but construction of commercial buildings of standard design (e.g., franchise restaurants and retail stores) will primarily involve assembly of manufactured components or installation of complete modules. To make school buildings more affordable to build and operate, such modular construction of schools may also become commonplace. Quality and material improvements, that cannot be afforded on a one-of-a-kind basis, will be assimilated into the high-volume manufacturing process.

Low-emissions construction materials and furnishings will be used in the building to reduce the energy used for ventilation as well as adverse health effects in occupants. Ventilation air will be filtered to remove infectious agents and allergens that cause illness in workers and lost productivity, and the use of recirculated air will be minimized. Individual controls will enable workers to adjust lighting to the most comfortable intensity for their work and for reduced glare. Daylighting will be more widely used to enhance worker satisfaction and comfort. "Best practice" commercial buildings will deal effectively with issues of moisture, thermal bridges, thermal distribution, air infiltration, and air quality.

By the year 2020, “best practice” buildings will also be delivering major performance improvements through the use of an integrated systems-oriented and optimizing design process. The energy performance improvements from an increased emphasis on design and commissioning will be accompanied by improved building energy services and lower overall first costs.

Improved information about building performance will allow informed design. Right-sizing and modular staged-operation designs with flexible uses and good part-load operating characteristics will reduce peak electrical demands as well as overall energy use. Information management systems for tracking equipment performance and status will ensure persistence of savings from energy-efficiency measures throughout the building life-cycle.

Larger commercial buildings will have many space conditioning equipment choices, including hybrid gas/electric space cooling systems and fuel cells for power generation, space and water heating, absorption cooling, and desiccant regeneration. Chlorofluorocarbon refrigerants will be completely removed from the buildings sector by 2020 and hydrogenated chlorofluorocarbons will be found only in older equipment.

The “best practice” commercial building will have highly-efficient centralized electric light sources combined with tracking daylight collectors connected to “piped” light distribution systems. In addition, natural lighting through windows and skylights will illuminate interior spaces during daytime hours.

Most new and existing buildings will use smart control technologies to optimize the building load configuration in response to weather, occupant demands, and utility rate structures. Natural conditions and building supply systems will be automatically balanced to adjust for predicted weather and occupant use. In order to permit greater use of the external environment to improve internal comfort conditions and reduce energy use, load control will also regulate the variable R-value wall panels and variable transmittance fenestration. Photovoltaic roofing shingles, wall panels, and awnings will contribute to the power requirements of state-of-the-practice commercial buildings.

The widespread use of "cool community" principles will mitigate the impact of urban heat island effects on major new developments and communities. In addition to reflective roofing and pavement, this may include using porous pavement, interspersing grass with concrete in lightly used parking areas, and installing grey water irrigation systems.

3.5 IMPROVEMENTS TO THIS ANALYSIS

There are a few areas where additional work could improve the accuracy of the calculations described in sections 3.2 and 3.3 above.

- Ducts in residential buildings typically leak 15-30% of the air passing through them. In addition, many of these ducts are inadequately insulated. The end result is that significant amounts of heating and cooling energy are wasted, particularly when ducts are in unconditioned spaces. A few relatively inexpensive measures (particularly the aerosol duct sealing technology) can reduce duct air and heat leakage significantly, even in existing buildings (Modera et al. 1996). Such measures are not included in the savings estimates for space conditioning equipment discussed above, and it is likely that an additional 0.5 to 1 quad of primary energy savings could be achieved by 2010 by widespread implementation in the residential sector.

- The savings estimates for commercial water heating and cooking, as well as for miscellaneous natural gas use, could be refined significantly. The data available on these end-uses are sparse.

- No savings have been estimated for commercial office equipment, but opportunities may arise to use voluntary programs (such as the highly successful ENERGY STAR office equipment program) to promote efficiency as this end-use evolves over the next decade.

- No savings have been included for commercial building shell measures. Windows strongly influence heating, cooling, and lighting loads in all commercial buildings, and insulation can be important for smaller commercial buildings.

- No savings have been included for ground source heat pumps in residential and small commercial buildings.

- No savings have been included for the advanced heat exchanger technology currently being commercialized by Modine, which reduces air conditioner and heat pump energy use by 15-20% and *reduces* the cost of the heat exchanger.

- No savings have been included for integrated systems that combine heating and water heating, or heating, cooling, and water heating.

- No savings have been included for district heating and cooling systems with combined heat and power.

- More data are needed on the effects of large-scale tree planting on energy use, and this policy option needs to be incorporated into the estimates of potential 2010 impacts.

- No credits have been calculated for downsizing of HVAC equipment associated with more efficient building shells.

- No attempt has been made to correct for changes in internal gains associated with energy savings for appliances located within conditioned spaces. Recent work in U.S. commercial buildings indicates that the heating penalties roughly offset the cooling benefits in both primary energy and dollar terms (when averaged across the entire commercial sector). There is no comparable analysis for average residences in the U.S., but an analysis for Europe (Krause et al. 1995) finds that this effect leads to small net energy penalties in residences.

- Because energy savings from miscellaneous electricity use are so important to the results of the buildings sector, it is crucial that more research be carried out, both to characterize how energy is used in the miscellaneous category and to identify technologies for improving the efficiency of sub-categories within the miscellaneous category of electricity use.

On balance, we believe that adding these items to the analysis would increase savings and decrease costs.

3.6 SUMMARY AND CONCLUSIONS

Our analysis leads to the following key results for 2010:

- The "efficiency" scenario results in 1.9 quads (5.3%) less energy use and 25 MtC (4.4%) fewer carbon emissions than the "business-as-usual" scenario in 2010. This represents a savings of $18 billion in fuel costs in 2010, which is purchased with an annualized incremental cost of $7 billion in efficiency improvements.

- The "high-efficiency/low-carbon" scenario results in 4.3 quads (12%) less energy use and 60 MtC (11%) fewer carbon emissions than the "business-as-usual" scenario in 2010. This represents a savings of $33 billion in fuel costs in 2010 resulting from an annualized incremental expenditure of $13 billion on efficiency improvements.

- In the residential sector, the greatest energy and carbon savings are achieved in miscellaneous electricity, lighting, space conditioning, and water heating. In the commercial sector, the greatest energy and carbon savings are achieved in miscellaneous electricity, space conditioning, and lighting.

- For both residential and commercial buildings, about 90% of the primary energy saved is electricity in both the "efficiency" and the "high-efficiency/low-carbon" scenarios.

- The time frame of the study (13 years) limits the penetration of efficiency technologies, because we only consider efficiency upgrades at the time of equipment retirement (no early retirements). About one-fifth of buildings sector primary energy consumption is not affected in our efficiency scenarios because the lifetimes of certain types of equipment are comparable to or longer than the analysis period (see Table C-2.11 in Appendix C-2). Savings from this “untouched energy” would eventually be achieved in our efficiency and high-efficiency cases, but only after 2010.

Six R&D areas offer great promise to reduce significantly the energy requirements in U.S. buildings in 2020:

- Advanced construction methods and materials will provide increased efficiency and improved building energy services, often with lower overall first costs. Construction methods in this time frame will consist primarily of factory-manufactured modules and components assembled on-site, enabling systems engineering to deliver greater energy efficiency, more affordable construction, and increased use of recycled materials. Building information management systems will improve life-cycle performance including feedback for continuous improvement in design.

- Environmental integration will produce buildings matched to the wide range of climatic conditions, and adaptive envelopes will capitalize on changing outdoor conditions to reduce energy use and improve occupant comfort and productivity. In addition, environmental integration strategies such as reflective roofing materials and turf paving will reduce urban heat island effects.

- Multi-functional equipment and integrated systems design offer the opportunity for a quantum leap in efficiency improvements. For example, combining the functions of several appliances into a single, highly effective device that puts to use waste heat and employs high-efficiency components to perform dual functions. Also, the use of integrated systems-oriented design and commissioning processes will provide efficiency improvements along with improved energy services and reduced first costs.

- Advanced lighting systems in 2020 will include a range of improved technologies such as improved controls; more high-efficiency small sources matched to improved luminaires; daylighting systems; and centralized sources with advanced distribution systems. Appropriate combinations of such systems will have the potential to employ highly efficient artificial light sources in combination with tracking sunlight concentrators, light pipes, and daylighting to meet the occupants' precise functional needs for lighting with an order-of-magnitude reduction in energy use.

- Controls, communications, and measurement capabilities will enable greatly reduced energy requirements by matching current and predicted weather conditions, utility rates, and internal environmental measurements to meet fluctuating occupant requirements while expending less energy.

- Finally, self-powered buildings will have fuel cells or small turbines, PV building components, and energy storage devices to provide building owners with new levels of flexibility in meeting their energy needs and generating revenues from electricity sales.

Achieving this promise will require significant R&D expenditures over the next twenty years, but will yield benefits that more than offset these expenditures.

3.7 REFERENCES

American Home Appliance Manufacturers. *AHAM Fact Book, 1996*, Chicago, IL.

Andrews, Steve. 1994. "Perry Bigelow: Energy Efficiency Maestro". *Home Energy*. March/April. p. 13.

Brown, R. E. 1994. *Estimates of the Achievable Potential for Electricity Efficiency Improvements in U.S. Residences*. In Proceedings of the 1994 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: American Council for an Energy-Efficient Economy. Vol. 7, page 55.

Brown, R. E. 1993. *Estimates of the Achievable Potential for Electricity Efficiency in U.S. Residences*. M.S. Thesis, Energy and Resources Group, University of California, Berkeley.

Christian, J. E. 1991. “Thermal Mass Credits Relating to Building Envelope Energy Standards,” *ASHRAE Transactions*, Vol. 91.

Darrow, C. 1994. “A House of the Future,” *The International Panel and Engineered-Wood Technology Exposition Conference Proceedings*, Atlanta, Georgia, October 5-7.

Energy Information Administration (EIA). 1996. *Annual Energy Outlook 1997, with Projections to 2015.* Washington, DC : U.S. Department of Energy, DOE/EIA-0383(97), December.

Energy Information Administration (EIA). 1995. *Emissions of Greenhouse Gases in the United States, 1987-1994*. Washington, DC: DOE Energy Information Administration, DOE/EIA-0573(87-94).

Fine, H. A. and D. L. McElroy. 1989. “Assessment of the Energy Conserving Potential of Active (Variable Thermal Resistance and Switchable Emittance) Building Thermal Envelope Systems,” *Thermal Performance of the Exterior Envelopes of Buildings IV, Dec. 4-7, 1989*. ASHRAE.

Hanford, J.W., J.G. Koomey, L.E. Stewart, M.E. Lecar, R.E. Brown, F.X. Johnson, R.J. Hwang, and L.K. Price. 1994. *Baseline Data for the Residential Sector and Development of a Residential Forecasting Database*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-33717.

Houghton, David J., Robert C. Bishop, Amory B. Lovins, Bristol L. Stickney, James J. Newcomb, Michael Shepard, and Bradley J. Davids. 1992. *The State of the Art: Space Cooling and Air Handling*. Competitek. August.

Kammerud, R. C. 1995. *Energy Use Impacts of Advanced Envelope Materials: Assessment of Mechanisms for Altering Radiation Absorptivity*. Oak Ridge, Tennessee: Oak Ridge National Laboratory, ORNL/Sub/86X-SP110V.

Komor, P. 1996. Cooling Demands from Office Equipment and Other Plug Loads. E-Source Tech Update TU-96-9. July 1996. Boulder CO. ESource.

Konopacki, Steven, Hashem Akbari, Mel Pomerantz, S. Gabersek, and Lisa Gartland. 1997. *Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas*. Ernest Orlando Lawrence Berkeley National Laboratory. LBNL-39433. May.

Koomey, J.G., C. Atkinson, A. Meier, J.E. McMahon, S. Boghosian, B. Atkinson, I. Turiel, M.D. Levine, B. Nordman, and P. Chan. 1991. *The Potential for Electricity Efficiency Improvements in the U.S. Residential Sector*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-30477.

Koomey, J. G., C. Dunham, and J. Lutz. 1994. *The Effect of Efficiency Standards on Water Use and Water Heating Energy Use in the U.S.: A Detailed End-Use Treatment.* Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-35475.

Koomey, J.G., F.X. Johnson, J. Schuman, E. Franconi, S. Greenberg, J.D. Lutz, B.T. Griffith, D. Arasteh, C. Atkinson, K. Heinemeier, Y.J. Huang, L. Price, G. Rosenquist, F.M. Rubinstein, S. Selkowitz, H. Taha, and I. Turiel. 1994. *Buildings Sector Demand-Side Efficiency Technology Summaries*. Berkeley, CA: Lawrence Berkeley National Laboratory, LBNL-33887.

Koomey, J. G., D. A. Vorsatz, R. E. Brown, and C. S. Atkinson. 1997. *Updated Potential for Electricity Efficiency Improvements in the U.S. Residential Sector*. Berkeley, CA: Lawrence Berkeley Laboratory, LBNL-38894 (DRAFT).

Koomey, J. G., and M. C. Sanchez. 1997. Trends in Carbon Emissions for Buildings. Submitted to Energy Policy in May, 1997.

Koomey, J. G., M. C. Sanchez, D. A. Vorsatz, R. E. Brown, and C. S. Atkinson. 1997. *The Potential for Natural Gas Efficiency Improvements in the U.S. Residential Sector.* Berkeley, CA: Lawrence Berkeley Laboratory, LBNL-38893 (DRAFT).

Krause, Florentin, Eric Haites, Richard Howarth, and Jonathan Koomey. 1993. *Energy Policy in the Greenhouse. Volume II, Part 1. Cutting Carbon Emissions Burden or Benefit?: The Economics of Energy-Tax and Non-Price Policies*. El Cerrito, CA: International Project for Sustainable Energy Paths.

Krause, Florentin, David Olivier, and Jonathan Koomey. 1995. *Energy Policy in the Greenhouse. Volume II, Part 3B. Negawatt Power: The Cost and Potential of Low-Carbon Resource Options in Western Europe*. El Cerrito, CA: International Project for Sustainable Energy Paths.

Lawrence Berkeley National Laboratory. 1996. *Draft Report on Potential Impact of Alternative Efficiency Levels for Residential Cooking Products*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Lawson, C. 1996. The Price of Commissioning Equals Cost Savings. ASHRAE Journal 38:1:30-34. Atlanta GA. ASHRAE.

Lovins, A. 1992. Energy-Efficient Buildings: Institutional Barriers and Opportunities. E-Source Strategic Issues Paper. SIP1. December 1992. Boulder CO. ESource.

Mills, Evan, and Arthur H. Rosenfeld. 1994. "Non-Energy Benefits as a Motivation for Making Energy-Efficiency Improvements". Presented at the American Council for an Energy-Efficient Economy (ACEEE) 1994 Summer Study on Energy Efficiency in Buildings in Asilomar, CA.

Modera, M.P., D.J. Dickerhoff, O. Nilssen, H. Duquette, and J. Geyselaers. 1996. "Residential Field Testing of an Aerosol-Based Technology for Sealing Ductwork". Presented at the ACEEE 1996 Summer Study on Energy Efficiency in Buildings in Asilomar, CA. Published by American Council for an Energy Efficiency Economy (also LBNL-38554).

Rosenfeld, Arthur H., Joseph J. Romm, Hashem Akbari, Melvin Pomerantz, and Haider Taha. 1996. "Policies to Reduce Heat Islands: Magnitudes of Benefits and Incentives to Achieve Them". Presented at the ACEEE 1996 Summer Study on Energy Efficiency in Buildings in Asilomar, CA. Published by American Council for an Energy Efficiency Economy.

Rosenfeld, A. H., J. J. Romm, H. Akbari, and A. C. Lloyd. 1997. "Painting the Town," *Technology Review*, February.

Sanchez, Marla. 1997. Miscellaneous Electricity Use in U.S. Residences. Master's Thesis (MS). University of California, Berkeley, Energy and Resources Group.

Schwolsky, Rick. 1997. "Positive Tradeoffs". *Builder Magazine*. January. p. 332.

Sezgen, A. O., E. M. Franconi, J. G. Koomey, S. E. Greenberg, and A. Afzal. 1995. *Technology Data Characterizing Space Conditioning in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0*. Berkeley, CA: Lawrence Berkeley Laboratory, LBL-37065.

Sezgen, A. O. and J. G. Koomey. 1995. *Technology Data Characterizing Refrigeration in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0*. Berkeley, CA: Lawrence Berkeley Laboratory, LBL-37397.

Shepard, et al. 1995. Commercial Space Cooling and Air Handling Technology Atlas. June 1995. Boulder CO. ESource.

Smith, J. A. and J. D. Rivera. 1989. "Beyond the Year 2000: A Broad Analysis of the Future Trends that will Affect Buildings," *Buildings of the 21st Century: Developing Innovative Research Agendas*, Gersau, Switzerland, May 16-18.

Todesco, G. 1996. Super-Efficient Buildings: How Low Can You Go? ASHRAE Journal. 38:12:35-40. Atlanta GA. ASHRAE.

U.S. Department of Commerce. 1996. *Statistical Abstract of the US*. Washington, DC: Economics and Statistics Administration, Bureau of the Census.

U.S. Department of Energy (DOE). 1990. *Technical Support Document: Energy Conservation Standards for Consumer Products: Dishwashers, Clothes Washers, and Clothes Dryers.* Washington, DC: DOE, DOE/CE-0299P.

U.S. Department of Energy (DOE). 1993. *Technical Support Document: Energy Efficiency Standards for Consumer Products: Room Air Conditioners, Water Heaters, Direct Heating Equipment, Mobil Home Furnaces, Kitchen Ranges and Ovens, Pool Heaters, Fluorescent Lamp Ballasts, and Television Sets.* Washington, DC.: DOE, DOE/EE-0009.

U.S. Department of Energy (DOE). 1995. *Technical Support Document: Energy Efficiency Standards for Consumer Products: Refrigerators, Refrigerator-Freezers, & Freezers*. Washington, DC: DOE.

Vorsatz, D. A. and J. G. Koomey. 1997. *The Potential for Efficiency Improvements in the U.S. Commercial Lighting Sector*. Berkeley, CA: Lawrence Berkeley Laboratory, LBNL-38895 (DRAFT).

Webber, C. 1997. Personal Communication regarding LBNL Technical Analysis of Reduction of Standby Electricity Use in Televisions and Video Cassette Recorders. Berkeley, CA: Lawrence Berkeley National Laboratory.

Wendt, R. L.. 1994. "Housing 2020: The Future of Wood in U.S. Dwellings," *The International Panel and Engineered-Wood Technology Exposition Conference Proceedings*, Atlanta, Georgia, October 5-7.

Westphalen, D., R. A. Zogg, A. F. Varone, and M. A. Foran. 1996. *Energy Savings Potential for Commercial Refrigeration Equipment*. Prepared by Arthur D. Little, Inc. for the Building Equipment Division, Office of Building Technologies, US Department of Energy. ADL Reference No. 46230.

ENDNOTES

[1] A "cost-effective technology" in our analysis is generally defined as a technology that is the minimum life-cycle cost option using a 7% real discount rate and the lifetime of the option. Life-cycle cost is the discounted sum of incremental capital costs and operating costs over the life of the option. This criterion is the equivalent of the cost of conserved energy equaling the value of displaced or saved energy.

[2] To determine which measures are less expensive than the average price of purchased fuel or electricity and hence cost-effective, we calculate cost of conserved energy (CCE) using the following equation:

$$\text{CCE (¢/kWh)} = \frac{\text{Capital Cost \%}\ \dfrac{d}{(1-(1+d)^{-n})}}{\text{Annual Energy Savings}}$$

where d is the discount rate and n is the lifetime of the conservation measure. The numerator in the right hand side of the equation is the annualized cost of the conservation investment. Dividing annualized cost by annual energy savings yields the CCE.

[3] Carbon emissions are derived from the product of end-use energy (by fuel) and carbon emissions factors of MtC/quad of primary energy taken from EIA (1996). The total cost of energy services is the estimated amount spent on energy consumption plus the incremental efficiency cost for purchasing and operating high-efficiency technologies. In the business-as-usual scenario, the incremental efficiency cost is defined to be zero.

[4] Miscellaneous energy use involves end-uses in buildings that are not currently allocated to other end-uses, namely refrigeration and freezing, space conditioning, lighting, cooking, drying, and water heating. In order to more accurately estimate energy savings potential, we divided the miscellaneous end-use into three electricity categories and two fuel categories. The three electricity categories were: electronics (e.g., color televisions and video cassette recorders), motors (e.g., fans and pumps), and heating (e.g., waterbed heaters, coffee makers, etc.). About 20% of miscellaneous electricity is associated with standby losses of equipment that are turned off but still draw a small amount of power (the so-called "leaking" component of miscellaneous). See Sanchez (1997) for more details.

[5] The scale for 2010 carbon emissions for electricity end-uses in Figures 3.2 and 3.3 is slightly different than shown for 1997, since a 2.5% decline in the carbon intensity of electricity generation is projected for 2010, but this does not significantly change the results shown in the figures. For example, residential miscellaneous electricity carbon emissions in 2010 are 92 MtC but appear slightly greater (~94 MtC) in Figure 3.2.

[6] The scale for 2010 carbon emissions for electricity end-uses in Figures 3.2 and 3.3 is slightly different than shown for 1997, since a 2.5% decline in the carbon intensity of electricity generation is projected for 2010, but this does not significantly change the results shown in the figures. For example, residential miscellaneous electricity carbon emissions in 2010 are 92 MtC but appear slightly greater (~94 MtC) in Figure 3.2.

[7] Major contributions to this section were made by George Courville, Mike MacDonald, Jeff Muhs, John Tomlinson, Jim VanCoevering, and Bob Wendt (Oak Ridge National Laboratory).

[8] Major contributions to this section were made by George Courville, Mike MacDonald, Jeff Muhs, John Tomlinson, Jim VanCoevering, and Bob Wendt (Oak Ridge National Laboratory).

[9] With thermal switching, the absorptivity and emissivity change between a high and a low value at a set material temperature; with short wavelength switching, the solar absorptivity changes at a specific wavelength radiation flux; and with long wavelength switching, the emissivity changes when the temperature of the radiative environment satisfies certain conditions.

[10] Heat pump water heaters are an exception to this general pattern. They have been demonstrated in the field to deliver up to three times as much energy in hot water as is provided to the unit in electricity; however, the technology's relatively high cost is a major market barrier. Technology breakthroughs could result in significant reductions in first costs, enabling greater market penetration of heat pump water heaters.